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(54) **Method of making biaspherical optical elements**

(57) A method of making biaspherical optical elements comprises compression firstly moulding hot glass in a die (not shown) to form a cylindrically shaped glass substrate 21 with two approximately accurate aspherical surfaces 33, 36, and subsequently coating each aspherical surface with a light transmissive polymeric material to form a substantially exact aspherical surface curvature and surface finish. The hot glass substrate 21 is removed from the die, cooled and located centrally between the respective mould halves 22, 23 of a master moulding tool whose moulding surfaces are prepared to a high degree of accuracy, filling each space between the respective aspherical surfaces 33, 36 of the substrate 21 and the adjacent moulding surface 34, 37 of the mould halves material 22, 23 with the polymeric material 32, 35 bonding the 32, 35 to the respective surface 33, 36 of the glass substrate 21 by the application of a minimal amount of heat and pressure which is just sufficient to mould the polymeric material 32, 35 without substantially raising the temperature of the mould halves 22, 23, and removing optical element so formed from the mould. The polymeric material 32, 35 is in foil form in Fig. 6. but can also be in liquid form (Fig. 7, not shown).

Fig. 6.

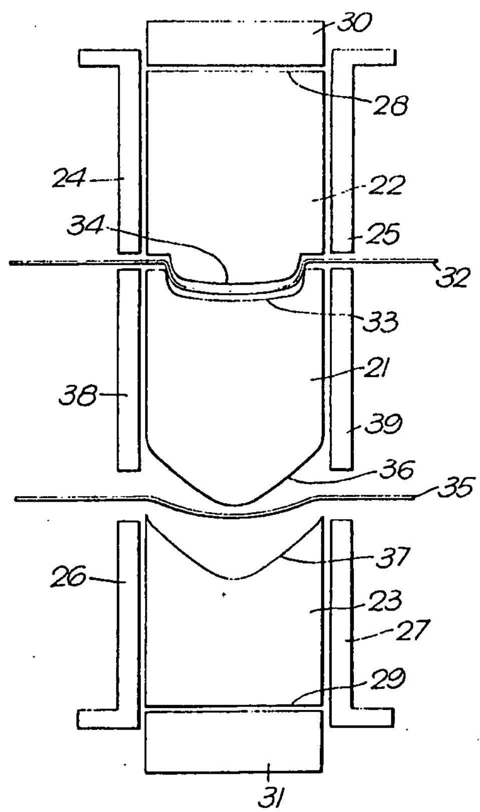

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Fig.1.

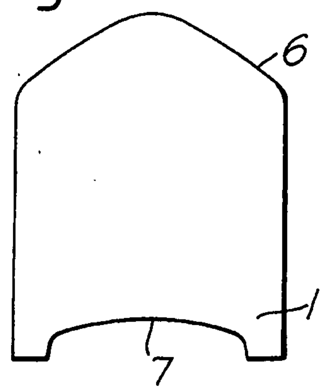


Fig.2.

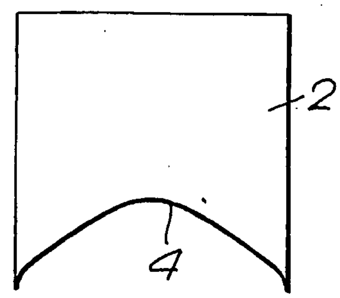


Fig.3.

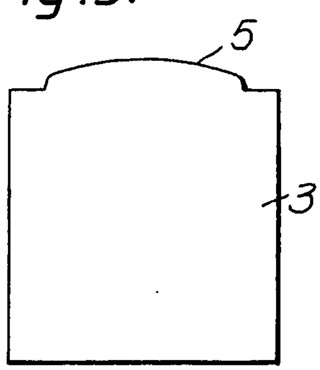


Fig.4.

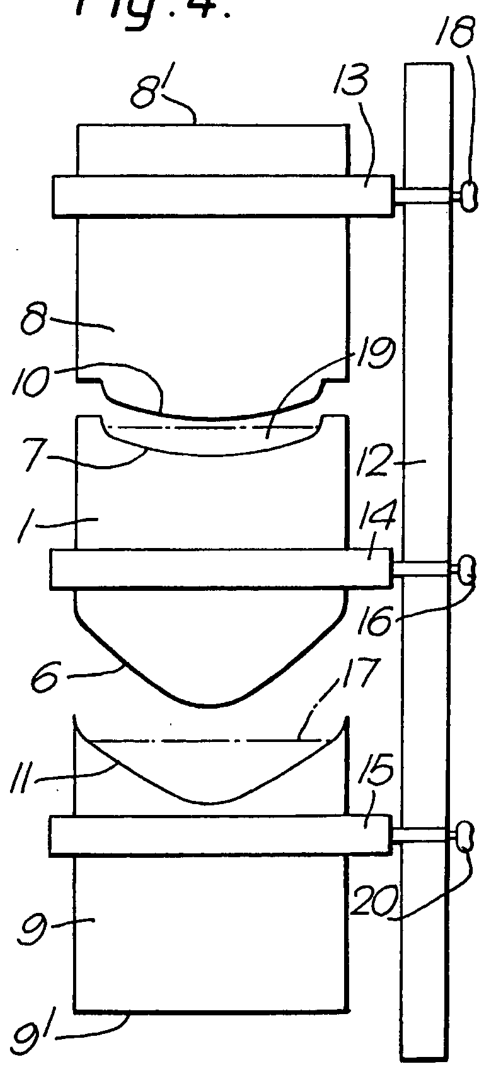


Fig.5.

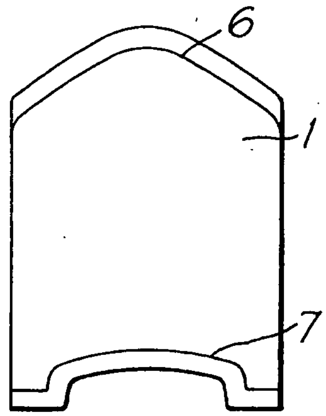


Fig. 6.

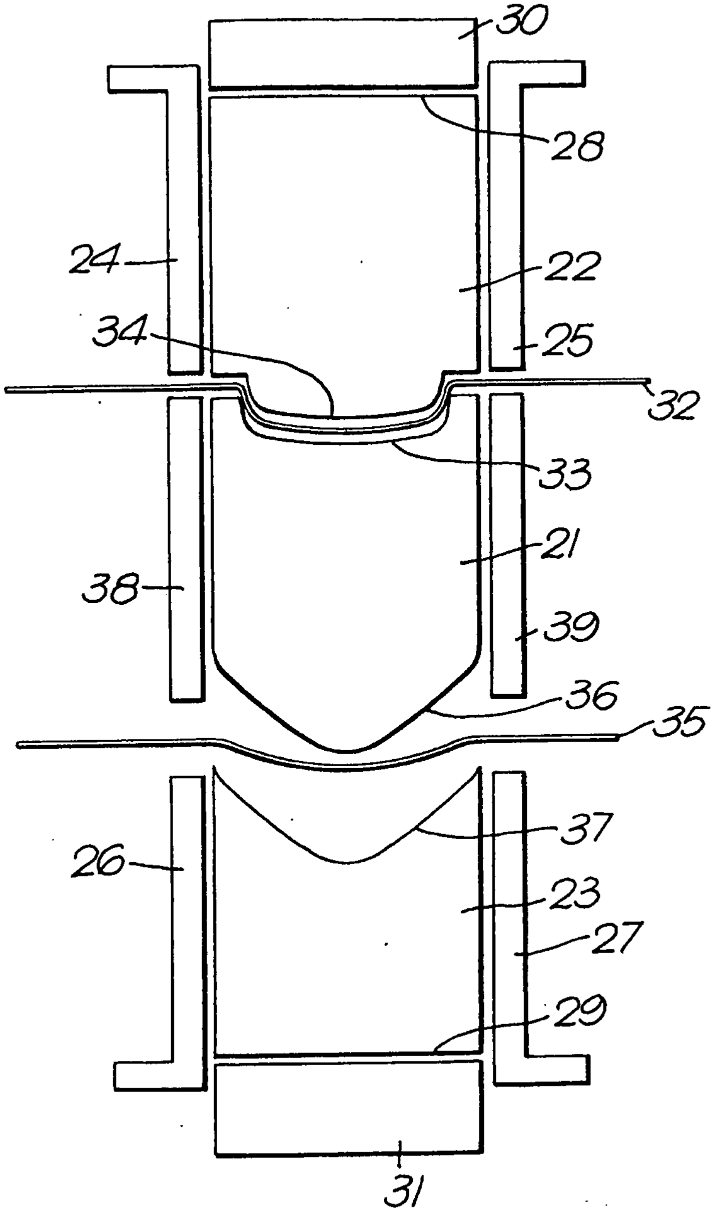
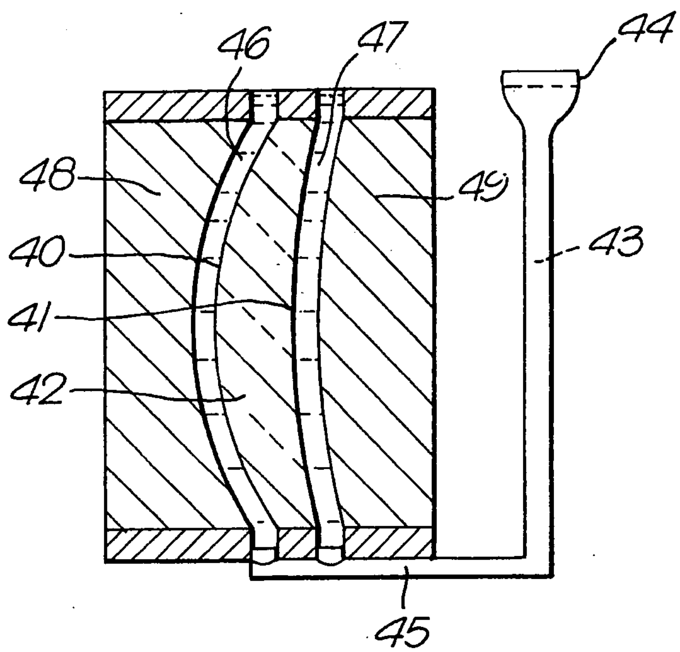


Fig. 7.



SPECIFICATION

Method of making biaspherical optical elements

The invention relates to a method of making biaspherical optical elements comprising compression moulding hot glass to form a glass substrate with at least one aspherical surface and treating the substrate to form a desired surface with a substantially exact aspherical curvature and surface finish.

Biaspherical optical elements with two aspherical surface curvatures are known and used, *inter alia*, in video and audio apparatus for recording information on or reading information from a track where the information is finely spaced along the track at one or more levels. It is known to press one or more glass blanks of hot glass when preparing the optical elements in which softened glass is pressed at a sufficiently elevated temperature in an accurately prepared heated die to form biaspherical optical elements. The surface of each element produced however has a second order of accuracy which surfaces decrease in quality with the number of articles produced. The surfaces may be separately processed in a second stage to form an optical element with a desired first order of accuracy by well known optical techniques of precision grinding and polishing on a lathe followed by hand figuring and polishing. This however, is time consuming and expensive and various methods of increasing both the quantity production and the accuracy of the surfaces produced have been attempted. These methods, in general, have been directed to the elimination of the expensive and time consuming hand figuring and hand polishing techniques commonly used and to the development of a single stage operation by the use of moulds or dies of high accuracy for moulding the hot glass at relatively low temperatures, that is at a temperature which is below normal to soften glass. Problems previously caused by the differential thermal expansion and contraction of very hot glass and of the various hot die components however are not avoided and furthermore damage to the die surface due to the hot molten glass sticking to the die surface still may occur. Compression moulding hot glass at its minimal low temperature even before mould damage occurs still has the disadvantage due to errors caused by the surface changes as a result of the volume coefficient of thermal expansion and contraction of the various die components used in the compression moulding process. These errors are not eliminated even at the lowest possible moulding temperatures and even when materials of low coefficient of expansion for both the glass and mould parts are used. The overall thermal expansion and contraction therefore still has to be estimated. An appropriate estimated correction may be made to the mould or die surface during manufacture. The estimated correction is furthermore limited by the need that the coefficient of expansion of the glass used should be greater than that of the die in order to assist a good release of the moulded glass from the die on cooling. A low moulding temperature for the glass furthermore has the disadvantage in that it results in a corresponding higher viscosity and a higher moulding pressure. This severely limits the choice of materials which are suitable for use as dies. Thus, only a few materials have the necessary suitable properties of hardness, resistance to deformation, an optical finishing capability and also good self releasing properties from fluid glass. The overall effect of moulding glass at the minimal low moulding temperatures, the high viscosity of the glass at the minimal softening point and resultant high moulding pressures also limits the length of life of the dies as well as strictly limiting the diameter size of the optical elements that can be produced because of the related pressure increases. Prior to the present invention only small biaspherical optical elements could be produced in small quantities to the required accuracy which is a few tenths of a micron surface curvature. A still further disadvantage is that with the use of high pressure moulding techniques great care must be exercised in order to avoid breaking the aforesaid expensive dies under the very high pressures used. Sudden variations in the moulding pressure and/or temperature have to be avoided and the moulding pressure has to be applied carefully over a uniform surface area in order to prevent fracture of the mould.

With care, glass blanks have been moulded at temperatures from about 250°C but this is inconvenient and does not lend itself to quantity production especially as a special non optical glass with a low viscosity at such a temperature is required for the glass blanks and also especially as special dies of high strength to resist the pressures involved, such as fused quartz, are required. U.S. Patent No. 4098596 describes a method of preparing an optical article from one special type of glass. In this method the pressures required for moulding the glass range from 4000 psi to 20,000 psi which pressure is required to be held for a period of time which is sufficient to replicate the surface smoothness of the die on the glass.

One object of the present invention is to provide a method for the manufacture of biaspherical optical elements in which each element has two substantially exact surface curvatures or curvatures of a first order of accuracy and surface finishes and wherein optical elements of any diameter size and comprising any viscosity grade optical glass can be made.

The expression "two substantially exact surface curvatures or curvatures of a first order of accuracy and surface finishes" for the purpose of the present invention refers to biaspherical optical elements wherein each finished surface has a curvature which does not deviate from the overall desired curvature by more than a few tenths of a micron at ambient temperatures and a smooth surface finish which is comparable to a conventionally produced, optically polished surface, that is, where the surface roughness as

high points have an arithmetical average deviation normal to a centre line of the curvature which does not exceed a few hundredths of a micron.

Another object of the present invention is to provide a method for the manufacture of biaspherical optical elements whereby glass blanks can be compression moulded from any conventional optical glasses to a surface curvature to within 5 microns of a desired curvature. A still further object is to provide a method whereby expensive dies can have a long life in use. Such dies can be made from a wide range of hard, inert materials. The die can be manufactured to a slightly oversized surface curvature of the desired shape and may comprise fused quartz, crystalline quartz, glassy ceramics, glassy (vitreous) carbon, metals or tungsten carbide. The hard, inert dies furthermore are not restricted to materials which have a low coefficient of thermal expansion but preferably by the degree of optical polish or smoothness of surface finish that can be reproduced on the complementary moulding surfaces at the temperatures and pressures of the glass moulding operations. Such hard, inert dies are satisfactory for use at temperatures up to 1000°C although the preferred moulding temperature is approximately 600°C at which temperature a softened glass has a low viscosity and a conveniently low moulding pressure which is sufficient to produce a good mould glass substrate for the biaspherical optical elements according to the invention to within at least 5 microns of the desired surface curvature accuracy required.

According to the present invention there is provided a method of making a biaspherical optical element comprising compression moulding hot glass to form a glass substrate with at least one aspherical surface and treating the substrate to form a desired surface with substantially the exact aspherical curvature and surface finish, characterised in that hot glass is compression moulded in a die to form a cylindrically shaped glass substrate with two aspherical surfaces, each surface having a curvature and surface finish of a second order of accuracy, removing the hot glass substrate from the hot die, allowing the glass substrate to cool, locating the glass substrate centrally between two mould halves of a master moulding tool, each mould half having a moulding surface which is substantially exactly complementary to the desired surface curvature and finish, filling each space between the respective end aspherical surfaces of the substrate and the surface of the adjacent mould half with a light transmissive polymeric material, applying a minimal amount of heat and axial pressure to mould the light transmissive polymeric material to each substrate aspherical end surface, the heat and pressure being just sufficient to bond the polymeric material to the respective aspherical end surface of the substrate without substantially raising the temperature of the adjacent surface of the mould half, stress relieving the polymeric material by allowing the heated polymeric material to cool by dissipation of the heat into each mould half prior to releasing the applied pressure and removing the glass substrate together with the polymeric material bonded thereto from the master moulding tool.

The die at the moulding temperature and pressure has the aforesaid long life in use and does not exhibit die release difficulties for hot glass. Furthermore, surface defects due to the hot glass sticking to the die surface were negligible. The glass was heated to a suitable softening point until it reached a conveniently low viscosity whence it was compression moulded in the die at a relatively low moulding pressure. The cylindrically shaped glass substrate was formed with an approximately accurate aspherical surface at each end. The cylindrically shaped glass substrate was removed from the hot die and allowed to cool. The surface of the glass substrate is then treated to convert it from a second order of accuracy to the desired exact aspheric profile and surface finish. Although it is desirable to have the surface finish of the die as smooth as possible for good mould release characteristics the surface of the die, and hence that of the glass substrate, does not have to be as smooth as required for the final optically polished finish. In order to convert the two surface curvatures of the cylindrical glass substrate to two exact aspherical curvatures each with the desired surface finish the glass substrate is located centrally between two mould halves of a master moulding tool. The master moulding tool, was previously prepared to a high degree of accuracy as measured at ambient temperatures, from a radiation transparent non metallic material. Suitable radiation transparent, non metallic materials are siliceous materials, such as, quartz, for example, crystalline quartz and fused quartz, silicate glasses and ceramics. Vitreous or glassy carbon can also be provided on the surface of the radiation transparent, non metallic master mould. The master mould tool comprises two mould halves at least one being transparent to radiant energy and wherein each mould half has an accurately prepared surface curvature with an optically polished, smooth surface which is accurate to the desired limits at ambient temperatures for example, to within 0.2 microns. When the polymeric material is contained in the space between the respective surfaces of the mould halves and the glass substrate a minimal amount of heat and pressure is applied which is just sufficient to bond the polymeric material to the glass substrate but without substantially raising the temperature of the appropriate mould halves. Preferably, the heat is applied as radiant energy axially through one or both mould halves at the same time as applying an axial pressure to effect the moulding. The radiant energy may be infra-red radiation, ultra violet radiation or microwave radiation. Microwave radiation is particularly preferred because the heating time can be restricted to a few minutes and the mould halves do not increase in temperature substantially during this time. Alternative light

radiations can be used for photosensitive polymerizable resins.

In one embodiment the light transmissive polymeric material comprises a thin thermoplastics foil which is heated to just below the glass transition temperature for less than 90 seconds. The polymeric material may be polymethylmethacrylate which is heated between non metallic mould halves in a microwave oven to between 120 to 180°C for less than 60 seconds.

In another embodiment the polymeric material is a liquid thermosetting resin which is heated, to its initial hardening stage, or partially cured stage, within 90 seconds before the application of axial pressure to mould the polymeric material. The liquid polymeric material was heated to 120°C for example in a microwave oven within 60 seconds before axial pressure was applied. In the case of the partially cured thermosetting resin the hardened resin can be removed from the mould prior to being fully cured. The layer of thermosetting resin after being fully cured on the glass substrate was at least 1 micron thick at the thinnest part and five microns thick at the thickest part.

The space between the moulding surfaces is controlled during the mould process by the application of the axial pressure to the mould halves in relation to the temperature and resistance of the polymeric material. In certain instances it may, for example, be convenient to use a resilient spacer foil which can be located at the periphery of the mould halves to assist in controlling the space between the moulding surfaces for example to not less than 1 micron and not more than 5 microns at the thickest part.

Preferably, the mould halves are both transparent to the applied radiant energy and also have a high-thermal capacity so that the local application of energy to the polymeric material is not sufficient to heat the adjacent mould halves substantially above ambient temperatures. The quantity of heat involved therefore can easily be dissipated by the mould halves without causing any dimensional change due to thermal expansion.

The mould halves may both be completely transparent to the radiant energy. However, it is understood that they do not have to be completely transparent to the radiant energy and in the case of microwave heating where very rapid heating takes place it may be desirable to allow the mould halves to absorb some of the radiant energy at least at the surfaces in order to effect good plastic flow of a thermoplastic material or to effect slow curing of a thermosetting resin on removal of the applied heat energy and pressure. In general, however, the mould halves do not reach a temperature greater than approximately 60°C and the polymeric material is moulded or cured, at a temperature less than 180°C.

The invention will be better understood by referring now to the following detailed description thereof, reference being made to the accompanying drawings in which:—

Figure 1 represents a cross-sectional view of a glass substrate for preparing a biaspheric optical element according to the invention,

Figure 2 represents a cross-sectional view of a concave die half of a compression moulding die with one aspherical polished die profile,

Figure 3 represents a cross-sectional view of a convex die half of a compression moulding die with another aspherical polished die profile,

Figure 4 illustrates a cross-sectional view of the glass substrate as shown in Figure 1 adjustably positioned between two mould halves,

Figure 5 represents a cross-sectional view of a biaspheric optical element when prepared according to the invention,

Figure 6 illustrates a cross-sectional view of one method of simultaneously preparing two biaspheric optical elements according to the invention by locating two glass substrates between two moulds and using two thermoplastics foils, and

Figure 7 represents a cross-sectional view of an apparatus in an alternative method for applying liquid polymeric material simultaneously to both faces of the glass substrate.

In accordance with the preferred practice of the invention the biaspheric optical element is prepared by first manufacturing the glass substrate 1 (Figure 1) by compression moulding a pellet of hot glass in a heated die (not shown) having two die halves 2 (Figure 2) and 3 (Figure 3). Each die half has a carefully prepared compression moulding surface curvature 4 and 5 respectively which curvatures are complementary to the approximate convex 6 and concave 7 curved surfaces of the glass substrate 1. The carefully prepared curved surfaces 4, 5 of the two die halves 2, 3 respectively are polished minimally to a degree of smoothness which smoothness need not exceed any subsequent modification or change of profile as the result of errors due to thermal expansion and contraction of the dies or as the result of the hot glass substrate on cooling. The surface curvature of the cold glass substrate was calculated in accordance with the coefficient of thermal expansion of the temperature for moulding the hot glass and allowing for the overall coefficient of expansion of the hot dies. The smoothness of the die surface did not limit the degree of smoothness of the formed glass substrate after pressing. By using a quartz die of a low coefficient of thermal expansion which has good mould release characteristics and by using glass pellets of an optical glass which can be heated to a low viscosity at a relatively low temperature so that a low compression moulding pressure was used, a large number of identical glass substrates (1) were produced with accurate surface curvatures which did not differ from the exact theoretical surface curvatures by more than one micron. The hot glass moulding die was suitably formed from crystalline quartz, fused quartz, a glass ceramic, glassy carbon or tungsten carbide. The die for moulding the hot glass melt was selected in accordance with the design considerations of the optical

element being made providing that the accuracy of the glass substrate (1) at the first stage of production was within a 5 micron tolerance. Problems associated with very low glass melt temperatures and high compression moulding pressures were therefore avoided and the possibility of damage or fracture of the die halves did not occur.

Figure 4 illustrates one glass substrate (1) positioned between an upper mould half 8 and a lower mould half 9 with moulding surfaces 10, 11 previously accurately prepared by hand polishing and hand figuring techniques. The surfaces 10, 11 were prepared to within 1 micron of accuracy to the desired complementary surfaces of the biasphere. A support member 12 with adjustable arms 13, 14 and 15 held the glass substrate 1 between the two mould halves 8, 9. The glass substrate 1 was positioned on the support member 12 so that the concave surface 7 was uppermost and the appropriate mould halves 8, 9 were positioned so that the concave surface 11 of mould half 9 was uppermost with the convex surface 10 of mould half 8 directed downwards. A small quantity of liquid polymeric material was placed in the centre of the respective concave surfaces 7 and 11 of the substrate 1 and mould half 9. The glass substrate was then lowered by releasing a fixing screw 16 so that the convex surface 6 contacted the quantity of liquid polymeric material 17 in the concave surface 11. The mould half 8 was then lowered by releasing the fixing screw 18 until the convex surface 10 contacted the quantity of liquid polymeric material 19 in the concave surface 7. A spacing member comprising a thin layer of a resilient polymeric material (not shown) was placed between the appropriate surfaces 7, 10 and 6, 11 around the periphery of the mould halves 8, 9 to ensure that the surfaces do not actually touch each other. A uniform pressure was applied axially to the ends of the moulds 8, 9 and the fixing screws 16, 18 and fixing screw 20 were tightened to clamp the component parts together. The adjustable arms 13, 14 and 15, and the fixing screws 16, 18 and 20 were preferably made of an insulative, non metallic material such as, plastics or wood as they were not heated when subjected to radient energy such as, microwave radiation. The mould halves 8, 9 are made from a radiation transparent, non metallic material which was polished to give the required surface smoothness and the required surface curvature of high accuracy. Quartz glassy ceramics, and glass carbon moulds were equally suitable.

Figure 6 illustrates a cross-sectional view of an apparatus in which a glass substrate 21 is located between upper and lower mould halves 22, 23. The upper mould halves 22, 23 are spaced apart and are each held by a pair of support members 24, 25. The lower mould half 23 is similarly spaced apart from the surface 36 of glass substrate 21 and is held by a pair of support members 26, 27. The support members 24, 25 and the support members 26, 27 are separately connected to a rigid frame (not shown). The upper mould half 22 and lower mould half 23 have their respective ends in contact with upper and lower platens 30, 31 respectively, of a press by which an axial force is applied. A thermoplastics foil of material 32 of at least five microns thickness is located between the concave surface 33 and the convex surface 34 of upper mould half 22. A similar foil 35 is located between the convex surface 36 and concave surface 37 of lower mould half 23. The platens 30, 31 can be moved under an applied pressure so that the thermoplastics foils 32, 33 between the respective surfaces 33, 34 and the surfaces 36, 37 are simultaneously deformed. The support members 24, 25 and 26, 27 may abut against resilient spacer members 38, 39 holding glass substrate 21 in order to limit the amount of deformation of the thermoplastics foils 32, 35. The surfaces of the mould halves 34, 37 can be treated with a mould release agent such as a thin, monomolecular layer of a silicone oil or an inert wax in a solvent in order to assist release of the mould halves after the thermoplastics foils 18, 37 are deformed to the desired contour and surface finish. The thermoplastics foil material is deformed into a permanent shape and high surface finish by the application of radiant energy, for example, by microwave radiation to heat the polymeric material without substantially raising the temperature of the mould halves 22 and 23 or the glass substrate 21.

Figure 7 illustrates in an alternative embodiment of the method the application of a polymeric material in liquid form simultaneously to both surfaces 40, 41 of a glass substrate 42. Liquid polymeric material 43 is contained in a reservoir 44 from which reservoir 44 the liquid polymeric material 43 passes *via* an inlet tube 45 to the appropriate space 46, 47 between mould halves 48, 49 respectively. When the spaces 46, 47 are filled with liquid polymeric material and are free from air bubbles the inlet tube 45 is disconnected and the polymeric material is cured at least partially in a rapid heating microwave oven. Heating of the polymeric material and associated mould halves 48, 49 did not occur for more than 60 seconds during which time the liquid polymeric material partially cured to form an initial set layer which was bonded to each face of the glass substrate under pressure applied axially to the mould halves 48, 49. The assembly was removed from the microwave oven and dismantled. The partially cured polymeric layers were allowed to fully cure in air over 24 hours and the surface curvature and surface finish matched the complementary surfaces of the mould halves to within 0.5 micron.

A microwave oven used to heat the polymeric material in the mould. Substantially only the polymeric material was heated in the following manner. The two mould halves clamped together as illustrated for example, by Figure 4 containing the glass substrate and the polymeric material was placed in a microwave oven which comprised

a totally enclosed rectangular cavity formed from aluminium sheet metal connected to a magnetron high frequency generator by a wave guide and a coupling slot. The rectangular cavity was proportioned so as to resonate at the under mentioned microwave frequency matched to the power feeder. Microwave heating of radar frequency radiation (12.5 cm wave lengths, 24 50 megacycles) was used. The energy absorbed by polar groups of the polymeric material decreased as polymerization proceeded. The two mould halves were formed from a non metallic material and were preferably highly polished fused quartz. Other suitable materials for the mould halves were crystalline quartz, glass, glass ceramic and glassy (or vitreous) carbon. The temperature of the polymeric material in each mould space was raised to about 120°C in less than 1 minute by a $1\frac{1}{2}$ kilowatt magnetron. The polymeric material only partially cured in this time and on pressing mould halves 48, 49 axially it formed a surface curvature shape and surface finish which was complementary to the moulding surfaces of each mould half. The mould was removed from the microwave oven and the residual heat contained in the polymeric material was allowed to dissipate to the mould. The mould (i.e. each mould half) did not increase in temperature to temperature greater than 30°C. Loss of accuracy of the surface of the mould due to thermal expansion and subsequent contraction was therefore minimal, the temperature of the mould did not attain more than 5°C above normal ambient temperatures. If desired the temperature of the mould can be reduced to ambient temperatures more rapidly by cooling means such as by blowing cold air or placing the die in thermal contact with a cold surface. Loss of accuracy of the surface of the polymeric material, after being removed from the mould and after being allowed to fully cure with time, was maintained at a minimal level and the resultant profile was found to match the surface curvature and surface finish of the mould to within a 0.2 μm tolerance band.

CLAIMS

1. A method of making a biaspherical optical element comprising compression moulding hot glass to form a glass substrate with at least one aspherical surface and treating the substrate to form a desired surface with substantially the exact aspherical curvature and surface finish, characterised in that hot glass is compression moulded in a die to form a cylindrically shaped glass substrate with two aspherical surfaces, each surface having a curvature and surface finish of a second order of accuracy, removing the hot glass substrate from the hot die, allowing the glass substrate to cool, locating the glass substrate centrally between two mould halves of a master moulding tool, each mould half having a moulding surface which is substantially exactly complementary to the desired surface curvature and finish, filling each space between the respective end aspherical surfaces of the substrate and the surface of the adjacent mould half with a light transmissive polymeric material, applying a minimal amount of heat and axial pressure to mould the light transmissive polymeric material to each substrate aspherical end surface, the heat and pressure being just sufficient to bond the polymeric material to the respective aspherical end surface of the substrate without substantially raising the temperature of the adjacent surface of the mould half, stress relieving the polymeric material by allowing the heated polymeric material to cool by dissipation of the heat into each mould half prior to releasing the applied pressure and removing the glass substrate together with the polymeric material bonded thereto from the master moulding tool.

2. A method according to Claim 1, in which the polymeric material is a thermoplastics foil which is heated to just below its glass transition temperature for less than 90 seconds.

3. A method according to Claim 1 or Claim 2, in which the polymeric material is polymethylmethacrylate which is heated between non metallic, mould halves in a microwave oven to between 120°C to 180°C for less than 60 seconds.

4. A method according to Claim 1, in which the polymeric material is a thermosetting resin in a liquid form which is heated to its initial hardening or partially cured temperature within 90 seconds before applying the axial pressure.

5. A method according to Claim 1 or Claim 4, in which the liquid thermosetting resin is raised to 120°C in a microwave oven in approximately 60 seconds, after which time the pressure is applied by non metal mould halves of the mould thereby causing the polymeric to take up the shape of each mould half, allowing the heat to dissipate and removing the substrate from the mould.

6. A method according to any one of Claims 1 to 5 in which a layer of polymeric material of at least one micron thickness is bonded to each aspherical end surface of the glass substrate.

7. A method according to any one of Claims 1 to 6 substantially as hereinbefore described.

8. A biaspherical optical element when prepared by the method according to any one of the Claims 1 to 7.

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